

SLENDER HIGH STRENGTH CONCRETE WALL BEHAVIOR PREDICTED BY FINITE ELEMENT ANALYSIS

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ABSTRACT

Slender concrete wall behavior subjected axially loading with eccentricity can be accurately predicted using non-leaner analysis application program FEA modeled on the experimental test procedure. Existing codes and research results are investigated to valid the analyzed results. Comparisons of the numerical results to established formula for the walls with opening reveals to be validated the accuracy of the FEA predictions; ultimate axial strength, load versus deflection curve, and failure made. The relationships of high strength concrete up to 150 Mpa and height to thickness until 50 with ultimate axial strength of slender walls are investigated using the FEA model.

KEYWORDS: *Slender High Strength Concrete walls, Axial Loaded with Eccentricity, Finite Element Analysis, Height to Thickness*

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INTRODUCTION

Background/Objectives

The increase use of slender concrete walls for high-rise building with high strength concrete led to trends of the wall design using second-order analyses. A second order analysis was permitted by the national code with little concern for stiffness and long-term serviceability. An alternate slender wall design method incorporated the combined load effects due to eccentric axial loads and the P-Δ effect. Strength requirements were considered so that chooses the amounts of reinforcement. Lateral deflection under service load was provided to give a reasonable limitation on the stiffness of the walls. The concrete slender wall behavior, especially deflections under service load will be predicted accurately in computing if a great deal of uncertainty as to what service loads actually are. Modeling the non-linear properties of concrete in finite element programs which simply rely on theoretical understanding has long been a difficult problem.

There is simplified empirical formula provided to predict the axial strength based on the experimental test results. The design equations given in the ACI318-2011 and AS3600-2010 are intended for axial load bearing walls supported top and bottom with eccentricity. The eccentricity within core of cross section led to whole section in compression. ACI318-2011,

$$P_{u,ACI} = 0.55f'_c A_g \left(1 - \left(\frac{kH}{32}\right)^2\right) \quad (1)$$

AS3600-2009,

$$P_{u,AS} = 0.6f'_c(t - 1.2e - 2e_a)L \quad (2)$$

While the equations give us to predict the ultimate axial load capacity, there are limitations the height to thickness ratio under 32 and opening sectional area under 20%. Apart from the introductory research of Saheb and Desay in 1990 on the slender walls with openings, Doh and Fragomeni proposed upgrade empirical formula which is covered the height to thickness ratio up to 40 as well as the concrete compressive strength until 100 MPa in 2012. The complex mathematical models to predict actual behavior is not substitute for actual full-scale tests when possible. The proposed formula and test results may be an excellent target to be theoretical model of the slender wall behavior subjected axially loading with eccentricity. Saheb proposed in 1990,

$$P_{uo,S} = 0.55f'_cA_g(1 - \left(\frac{kH}{32}\right)^2)(1.2 - \left(\frac{H}{10L}\right))(1.25 - 1.22\alpha) \quad (3)$$

Doh proposed in 2012,

$$P_{uo,D} = 2.0f'_c{}^{0.7}(t - 1.2e - 2\frac{k^2\beta H}{2500})L(1.175 - 1.188\alpha) \quad (4)$$

METHODS

The finite element model was constructed by the nonlinear analysis application program FEA produced by MIDAS. The 3D detail analysis considering concrete and reinforcement simultaneously using solid brick element defined the total strain crack model with elastic modulus in compression and brittle in tension is applicable. In smeared crack models a crack is conceived to be distributed over the area of an element represented by an integration point. The cracked concrete is considered as a continuum where the notions of stress and strain are defined. It is the constitutive relation can be described in terms of stress-strain relations. The constitutive relation in the uncracked state is restricted to linear-elasticity. After a tension cut-off criterion occurs the linear-elasticity relation is replaced by an orthotropic stress-strain law with the axes of orthotropic in accordance with the directions of the principal stresses.

In the extensive experimental test, slender concrete walls which have three kinds of height to thickness ratio 30, 35, and 40 were tested to failure so that derived more simplify empirical formula predicted the ultimate axial strength accurately. Typical details of the slender wall panels adopted in this study have one opening reduced 25% sectional area at the center of the walls. All concrete wall were reinforced with a single F41 mesh placed at the middle of the section had design yield strength of 450 MPa and reinforcement ratios of the vertical and horizontal were 0.0031 satisfying the minimum requirements for shrinkage cracks in accordance with the Australian Standards shown in Figure 1.

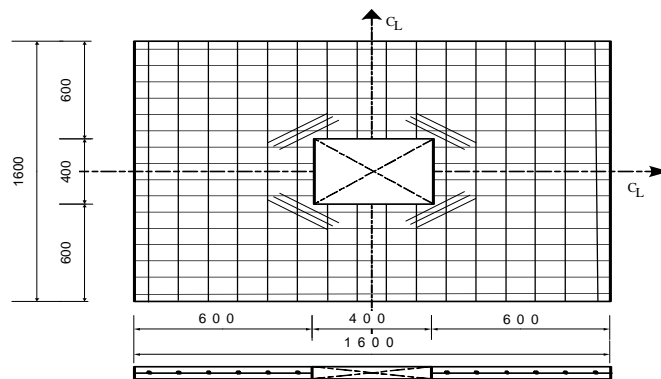


Figure 1: Reinforcement Details of Test Panel W40 (Units=mm)

Table 1: Experimental Results

Destination	Size (mm)	Opening (mm)	Height Thickness	fcm (MPa)	Pu,test (kN)	δ_{max} (mm)
W3050	1200	300	30	53.0	309.0	5.7
W3070	1200	300	30	67.7	426.7	6.3
W3090	1200	300	30	95.1	470.9	4.7
W30100	1200	300	30	96.2	488.5	6.8
W3530	1400	350	35	38.0	191.3	7.9
W3580	1400	350	35	80.0	300.2	4.2
W35100	1400	350	35	99.3	426.1	6.2
W4050	1600	400	40	47.0	294.3	5.3
W40100	1600	400	40	97.1	503.3	6.5

As indicated in Table 1, the concrete compressive strengths of the slender wall panels were from 38.0 MPa to 99.3 MPa obtained the average of three cylinder test result at the same testing day. The wall panels axially subjected uniformly with eccentricity by thickness over 6 up to failure measured load versus lateral deflection shown in Figure 2.

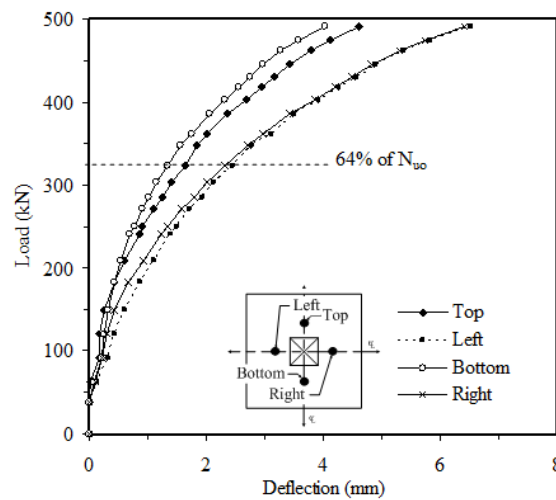


Figure 2: Load-Deflection Results of W40100



Figure 3: W35 Test Results

The wall panels supported top and bottom shown a typical single curvature bending failure characterized by the horizontal cracking at the center of the panels failed in a brittle mode in high strength concrete in Figure 3.

RESULTS

Ultimate Axial Strength

The ultimate axial strength of the wall panels of test results is compared with existing codes and research results as well as analyzed results by FEA. Code equations of ACI318 and AS3600 cannot be predicted by height to thickness over 32 but also for high strength concrete. These predictions are too conservative even though the opening effect was not concerned in case of the W30 series panels. Saheb and Desayi equation can be suggested the ultimate strength additionally concerned opening effect but the suggestion also has the height to thickness limitation and conservative results. Doh and Fragomeni equation can be successfully predicted. Comparison with test result shows almost identical indicated in average 102.2% with standard variation 17.8%. However, the predicted ultimate axial strength by the simply empirical formula should not exceed the test results due to uncertainty. Even though comparison of FEA results shown average 89.3%, all the case of wall results not exceed with small standard deviation within 6.8% listed in Table 2.

Table 2: Comparison with Existing Equations and Analyzed Result

Destination	Pu,test (kN)	Pu,eq.1 [*] (kN)	Pu,eq.2 ^{**} (kN)	Pu,eq.3 ⁺ (kN)	Pu,eq.4 ⁺⁺ (kN)	Pu,FEA (kN)
W3050	309.0	169.4	122.1	179.6	290.1	246.2
W3070	426.7	216.4	156.0	228.3	344.3	400.2
W3090	470.9		219.1	319.1	436.7	450.1
W30100	488.5		221.6	322.8	440.3	467.2
W3530	191.3				240.4	148.2
W3580	300.2				404.8	276.1
W35100	426.1				470.9	372.7
W4050	294.3				285.8	278.1
W40100	503.3				475.0	441.9

^{*} eq.1; ACI318; $P_u = 0.55f_c A_g (1 - (kH/32t)^2)$; $k=1$, $f_c < 65\text{MPa}$

^{**} eq.2; AS3600; $P_u = 0.6f_c (t - 1.2e - 2e_a)L$; $e_a = H^2/2500t$, $f_c < 100\text{MPa}$

⁺ eq.3; Saheb&Desayi; $P_{uo} = (1.25 - 1.22x)P_u$; $P_u = 0.55(f_c A_g + (f_y - f_c)A_{st})(1 - (H/32t)^2)(1.2 - (H/10L))$; $f_c < 45\text{MPa}$

⁺⁺ eq.4; Doh&Fragomeni; $P_{uo} = (1.175 - 1.188x)P_u$; $P_u = 2.0f_c^{0.7}(t - 1.2e - 2ae_a)L$; $\alpha = \sqrt[3]{18/(H/t)^{0.88}}$ for $H > 27$; $f_c < 100\text{MPa}$

The comparison of ultimate strength of every equation with tested result shows in Figure 7 and regression analysis of the comparison indicates linear relationship by 0.91 sloped and calculated R square value 0.9626.

Load Versus Deflection

Maximum load versus deflection curves of all the wall panels are compared with the graph analyzed by FEA at the identical place on the wall panels described between Figure 4 and Figure 6. The analyzed deflections of the wall panels at the fail compared with test results show a little big difference calculated standard deviation over 20.2% due to the tested deflection value observed by a dial gage visually at the loading interval. In spite of the difference of deflection at the fail, the graph trend of every panels show closely identical.

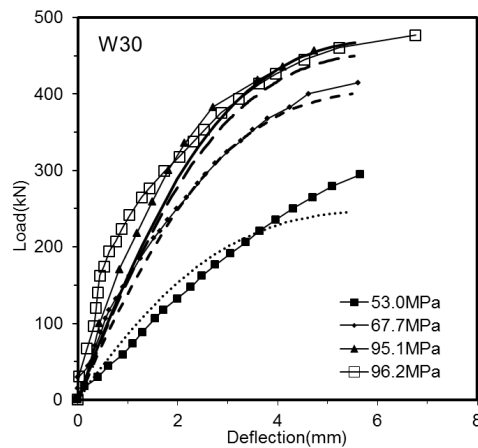


Figure 4: Comparison between FEA and Test Results of W30

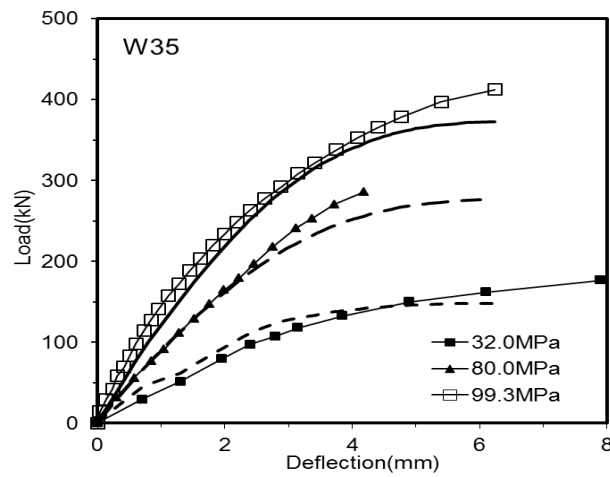


Figure 5: Comparison between FEA and test results of W35

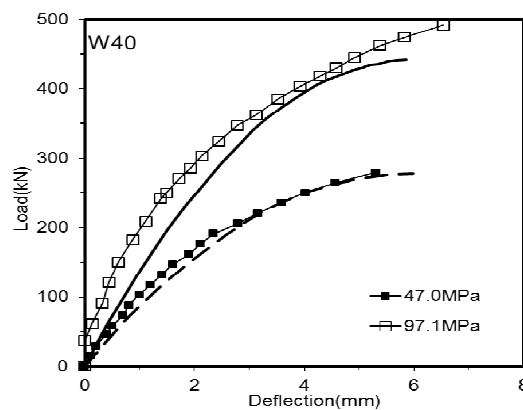


Figure 6: Comparison between FEA and test results of W40

Curvature

The typical deflected wall shape analyzed by FEA indicated in Figure 8. Cracks occur tension face for normal concrete strength in a flexure mode and compression face for high concrete strength in a brittle mode. During the test procedure, it is sometimes difficult to observe the maximum deflection precisely at failure. The cracks can be observed in detail under FEA procedure.

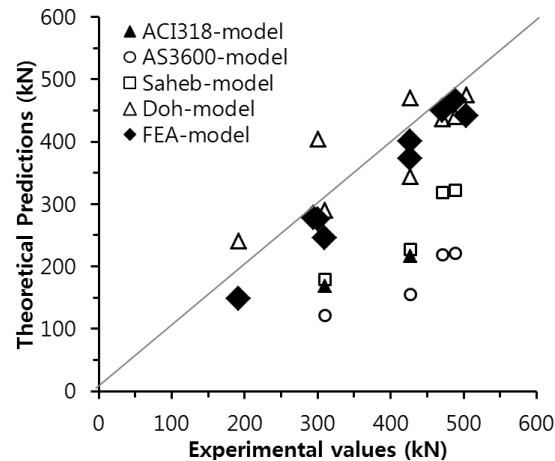


Figure 7: Ultimate Loads Predicted by FEA and Equations Compared to Test Results

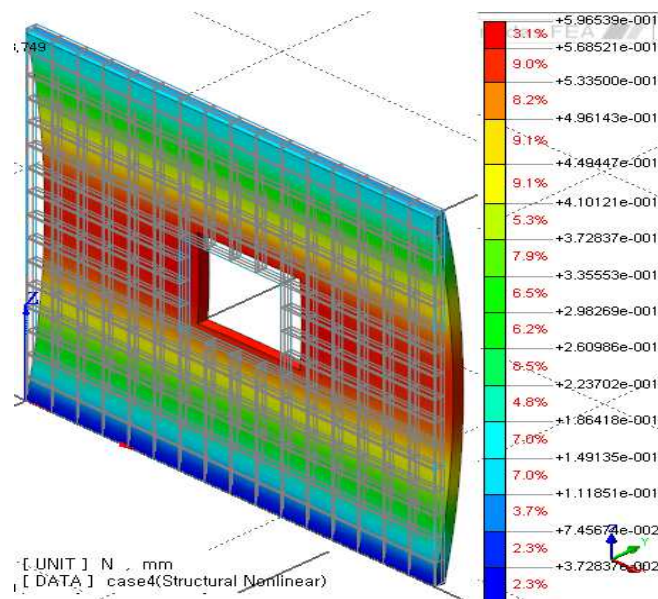


Figure 8: Lateral Deflection of W40 Predicted by FEA

Predictions of Concrete Strength and Height to Thickness Ratio

As the concrete strength varying up to 150 MPa using FEA, the nominal axial strength of walls ($P_{uo}/f_c A_g$) shows to decrease along $-0.028 \ln f_c + 0.2184$ indicated in Figure 9. The relationship is placed below the Doh equation and exist test results to be safe predictions while the Saheb equation placed to be too much conservative.

As the height to thickness until 50 using FEA, the nominal axial strength of walls shows to be identical with the Doh's prediction while the Saheb equation has a limitation of applicable range in Figure 10.

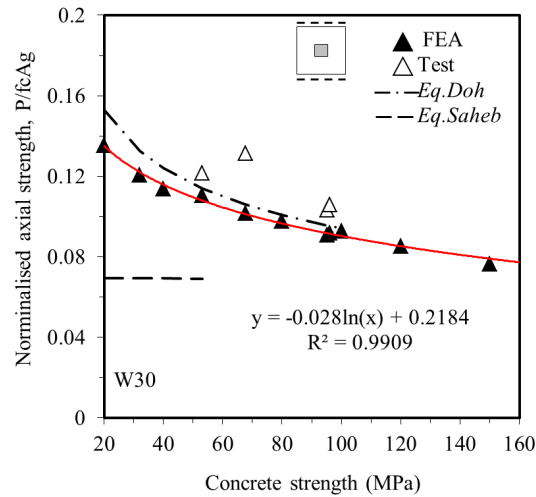


Figure 9: Predictions of Axial Strength of walls for Height to Thickness

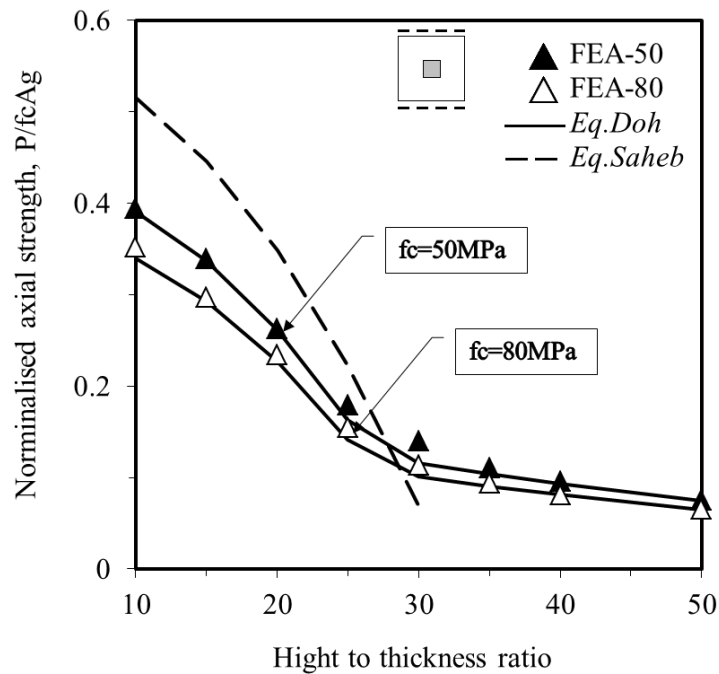


Figure 10: Predictions of Axial Strength of Walls for Height to Thickness

CONCLUSIONS

An experimental test was modeled by FEA program on a total of nine concrete slender wall panels with one opening at the center. Axially loaded wall panels with an eccentricity of thickness on 6 had high height to thickness between 30 and 40 in which range buckling failure occur by existing code shows available strength in the numerical results. Ultimate strength and deflection of walls matched with test results to be reasonable identical. The failure mode and crack propagation also can be predicted.

ACKNOWLEDGEMENTS

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REFERENCES

1. ACI318, *Building Code Requirements for Reinforced Concrete*, American Concrete Institute, Detroit, USA, 2011.
2. AS3600, *Concrete Structures*, Standards Australia, Sydney, Australia, 2010.
3. C. Popescu, G. Sas, T. Blanksvard and N. Yaljesten, *Concrete walls weakened by openings as compression members: review*, *Engineering Structures*, Elsevier, Vol. 89, 172-190, 2015.
4. D.J. Lee, S.T. Oh, Y.S. Kim and S.H. Jeong, *Slender concrete wall behavior predicted by finite element analysis*, *Annual Conference Engineering and Information Technology*, ACEAIT-7384, 438-446, 2015.
5. S. Fragomeni, J.H. Doh and D.J. Lee, *Behavior of axially loaded concrete wall panels with openings: an experimental study*, *Advances in Structural Engineering*, 15(8), 1345-1358, 2012.
6. S. M. Saheb and P. Desayi, *Ultimate strength of R.C. wall panels with opening*, *Journal of Structural Engineering*, ASCE 116(6), 1565-1578, 1990.